**Omnidirectional Antenna Design for Underground Wireless Sensor Networks**

Khomotso C. Tsoane Topside E. Mathonsi Deon P. Du Plessis

*Department of IT Department of IT Department of IT*

*Tshwane University of Technology Tshwane University of Technology Tshwane University of Technology*

Pretoria, South Africa Pretoria, South Africa Pretoria, South Africa

[Tsoanekc@gmail.com](mailto:Tsoanekc@gmail.com) [ManthonsiTE@tut.ac.za](mailto:ManthonsiTE@tut.ac.za) [DuPlessisDP@tut.ac.za](mailto:DuPlessisDP@tut.ac.za)

***Abstract—* an omnidirectional antenna is proposed for the underground Wireless Sensor Networks (WSNs) intrusion detection. The Square Slotted Monopole Antenna (SSMA) was used during the design of the proposed omnidirectional antenna. The proposed antenna is square-shaped with 20 mm sides. This was done in order to improve the detection accuracy. The electromagnetic simulator namely Ansys High-Frequency Structure Simulator (HFSS) was used to implement the designed omnidirectional antenna. A micro-etching machine on the low-cost substrate was used during the proposed omnidirectional antenna evaluation. The Ansys HFSS results showed the proposed omnidirectional antenna has high-frequency depth, increased dispersion of the transmitted signals as well as their spreading. For a depth of 30 cm, the omnidirectional antenna has shown an average fidelity of 0.9 and a spread factor of 1.5.**

***Keywords: Fidelity, Intrusion Detection, Underground Wireless Sensor Networks, Omnidirectional Antenna, Square Slotted Monopole Antenna, Spread Factor.***

# i. Introduction

The antenna is a significant component in a communication chain. As a result, its design must meet the specific requirements of the application. Thus, for Ultra-Wide Band (ULB) applications, the main difference between a ULB antenna and a conventional narrow band antenna is the bandwidth [1]. The difference between ULB and conventional antenna technologies also lies in the ability to detect underground unusual circumstance and send nonfiction in the required time. The review of literature has shown that conventional antenna does less to prevent cable theft. Connected motion sensors goes steps ahead to detect any movement, and impact of an object using active ultrasonic and pyroelectric infrared (PIR). A connected active ultrasonic sensors and passive infrared sensors technologies, both of which are known for their accuracy and reliability [2]. The ULB antenna technology allows the motion sensor to automatically detect incoming commotions and triggers an alarm in order to scare the theft. The motion sensor technology, therefore attempts to prevent copper theft more than a typical surveillance camera. However, the use of sensor surveillance cameras with motion has many drawbacks such as transmitters associated with narrowband sub-GHz systems are not energy efficient since their oscillators and power amplifiers use high power voltage to generate continuous signals. Other Wireless Sensor Networks (WSNs) technologies seem outdated as they use localisation capability; for some applications, the localisation of sensors is important and it may be interesting to take advantage of the radio link to perform this localisation [3 - 4]. But the accuracy of the distance estimates is all the better as the bandwidth of the radio signal is large. These limitations are a hindrance to the large-scale use of underground WSNs, hence the interest in studying an alternative approach.

This paper proposed to integrate the pulsed ULB technique with an underground WSNs. The main motivations for using ULB technology in the proposed solution; also according to Barras [5] are; 1) Reduction of the size of the antennas: this technique makes it possible to reduce the dimensions of the antennas used and thus reduces the size of the modules and costs while simplifying their deployment. 2) Limitation of power consumption: the transmission powers allowed in ULB are very low, which favours a longer lifespan of the underground sensors. Moreover, ULB transceivers are easy to integrate with low-power CMOS technology. 3) Localisation capability: the pulsed ULB technique, with its very wide bandwidth, is expected to provide these systems with good localisation accuracy. 4) Increased communication rates are possible, as the capacity of the communication channels increases with their bandwidth. The main foreseeable limitation of the use of the pulsed ULB technique in the shallow underground depth of the antennas.

The rest paper is structured as follows: Section II, presents the related work. Section III, shows the design of the omnidirectional antenna using ULB technology. The paper also presents simulation results that compare the efficiency of the novel omnidirectional antenna with the traditional directional antenna used in underground WSNs.

II. RELATED WORKS

Studies have already been carried out, including the use of buried antennas, to analyse the effect of the ground on the antenna or on the propagation in the ground. These studies have generally been carried out in the narrow band at frequencies below 1 GHz. For example, the design and performance study of four UHF antennas underground in concrete and operating at 392.5 MHz was presented by Barras [5]. These antennas are: a 16.7 cm horizontal dipole, a 38.5 cm diameter ring, a 150 cm long travelling wave monopole with a 76 cm diameter disk ground plane, and a 150 cm long V-shaped travelling wave monopole with a 43 cm diameter disk ground plane. These antennas were free-space matched at 1 GHz to operate correctly at the desired frequency in concrete with a dielectric constant of 6.5 [5].

Das, Mohanty and Mishra [9] studied the effect of soil on 145 MHz resonant antennas buried at shallow depth. The results show a shift of the resonant frequency to lower frequencies and degradation of the efficiency. A rectangular microstrip antenna, 49 x 29 x 3 mm3, buried in the ground for dual use: moisture measurement at 1.85 GHz and communication with an external reader at 1.35 GHz is presented by Saeidi et al. [11]. The results show a 130 MHz shift in resonant frequency, towards the lower frequencies, when the buried antenna is moved from dry soil to soil with 25% moisture. In [14], an Archimedean spiral antenna printed on a 87 x 87 x 1.5 mm3 square substrate, operating in the 1 - 3 GHz band and intended to be buried in the ground to measure its dielectric properties, is presented. The results obtained with this antenna, buried in ice, show a reduction of its input impedance, degradation of its efficiency, and an increase in its directivity. A rectangular broadband antenna, 67 x 42.5 x 1.54 mm3, for in-ground transmissions is reported in [10]. In free space, this antenna is matched in the 1.32 - 3.94 GHz band, which allows it to operate in the 0.869 - 2 GHz band when buried in dry soil [11]. All the works cited show the strong influence of the ground on the performance of the buried antenna. The most important observation is the shift of the bandwidth towards low frequencies. This observation will allow the design of small antennas to be buried in the ground.

In Norway, WSNs system was deployed in a moving glacier to monitor its variations in position, temperature, pressure, and conductivity [6]. The system consists of four main components: sensors (or probes) underground in the glacier to a depth of 100 m, a base station placed on the surface of the glacier above the probes, a reference station located in the valley 2.5 km away, and a remote server connected to the reference station and accessible via the web. To facilitate communication between the base station and the sensors, a transmitter and receiver (relay) connected by cable to the base station was underground 30 m deep in the ice. The communication between the sensors and this relay is done through the ice by radio link at 433 MHz and with a power of 100 mW. The long distance link between the base station and the reference station is made in the air at 468 MHz and with a power of 500 mW. However, the results presented in this study relate to the physical parameters of the glacier and not to the characteristics of the propagation channel [6]

A snowy environment study was performed on the possibility of using the ULB technique in WSNs to locate avalanche victims was resented [7]. A propagation model in a snowy environment was proposed and then experimentally validated, in the 3.3 to 4.6 GHz band, by estimating the permittivity of the snow. Then a theoretical study based on the proposed model was carried out to estimate the attenuation as a function of distance, at frequencies of 0.5 GHz and 3.8 GHz. The water contents considered are VWC = 2.3%, 6.4% and 12.1%. The underground depth of the transmitting antenna and the height of the receiving antenna are both considered equal to 1 m. The results show that increasing the frequency and water content of the snow results in large attenuations. At 3.8 GHz, the attenuation is -131 dB at 10 m separation for VWC = 6.2%, and 90.1 dB at 20.2m separation for VWC = 2.3%. While at 0.7 GHz, the attenuation is 63 dB at 31m separation for the worst case of VWC = 12% [4]. Though, given that the designed WSNs a traditional omnidirectional antenna, significantly affected the normal operation of the WSNs regarding peripheral coverage, low signal and distance coverage, and security issues. Besides, the WSNs had a low beam-width [7].

A WSNs to counter cable theft for copper cable using a microcontroller and GSM-supported antenna was designed by [8]. In the design, the antenna was embedded with an electrical circuit wire connection to detect voltage drop of the cable via the microcontroller antenna input port. Similarly, to the directional antenna proposed by [8] microcontroller antenna generated a wide operating band to cover the DVB-H band through the UHF frequency, which was effective for underground theft detection. The antenna was supported with an LEC display screen and mobile phone assembly for robust analysis and visualisation of incoming data in the underground environment [16].

III. METHODS

1. *Numerical measurement*

The proposed solution cycle is made up of four periods, the duration of which can be configured. The duration of a cycle varies according to the duration parameters of each period of activity and the number of coordinators. For the interval [T1; T3], the unit of time used is the slot of detection activity. A basic WSNs slot has 60 symbols (3 back off periods) or 960 μs. The slot duration exponent (EDS), the equivalent of the Super frame Order of the standard IEEE 802.15.4, allows to size the duration of the activity slots as follows:

|  |  |
| --- | --- |
|  | (1) |

The synchronization period [T0; T1]: The duration of the synchronization period depends on the number of *nbC*coordinators and the duration Tb of a sending interval of beacon expressed in *ms* . Tb is such that:

|  |  |
| --- | --- |
|  | (2) |
|  | (3) |

This paper calculated the duration of the synchronization period according to the number (*nbC*) of coordinators using the following formula:

|  |  |
| --- | --- |
|  | (4) |

The duration of [T1; T2] depends on the length of the period of activity of each star and the number of stars in the network. The duration of the period of activity of a Star is the same for all stars in the network: it is composed of a period intra-star and a relay interval. The duration of the intra-star period of intra, expressed in *ms*, can be configured by setting *nbS*the number of activity slots for this interval (depending on the load generated by all the sheets). The routing period [T2; T3]: The duration of [T2; T3], expressed in *ms*, depends on a load of non-priority traffic. [T2; T3] is configurable by setting nbSR the number of activity slots for the routing period and has two guard periods. We have so:

|  |  |
| --- | --- |
|  | (5) |

Sleep period [T3; T0]: The duration of [T3; T0] determines the period of inactivity during which all network entities are dormant. Cycle duration: The duration of a detection cycle, expressed in *ms,* is determined by adding the length of the four periods as shown in equation (6).

|  |  |
| --- | --- |
|  |  |

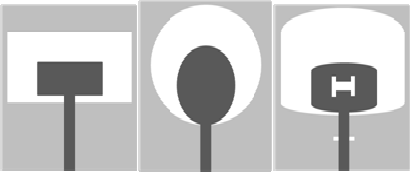
1. *Simulation Environment*

Two 3D electromagnetic computers, allowing the design and simulation of antennas; namely HFSS (High Frequency Structure Simulator) (Computer Simulation Technology) was used. It is on this software that the study chose to perform antenna design and related network simulation. The electromagnetic simulator is based on several techniques [17]: the finite element method (FEM) and combines the staircase and hexahedral meshing methods to approximate as closely as possible the real shape of the structure to be studied. Thus, depending on the needs of the simulation, the most appropriate method is used [17]. The temporal simulation with CST allows obtaining different results in time and frequency domains such as time signals, S-parameters, 2D and 3D radiation patterns, and electromagnetic fields in time and frequency. These capabilities and performances are well suited for UBL calculations hence our choice. After making the above mentioned choices, this paper designed the ULD omnidirectional antenna which we then used for the analysis of the underground intrusion detection.

IV. EXPERIMENTAL RESULTS

## *Omnidirectional antenna measurement and design*

The design structure of the SSMA is a planar antenna with a large slot in the ground plane. This type of structure provides antennas with wide bandwidth and easy integration. Two rectangular and triangular slot antennas, 12×12 cm2, are presented. Both antennas have wide bandwidths of 130% (1.82 to 7.14 GHz) and 105% (2.31 to 8.18 GHz), correspondingly. An octagonal slot antenna with a bandwidth of 102% (2.91 to 9.09 GHz) is presented [9]. A wide E-slot antenna with 85×85 mm2 and 120% bandwidth (2.8 to 11.4 GHz) with a circular wide slot antenna, 80×80 mm², and attaining a bandwidth of 150% (1.7 to 10.5 GHz), is presented.

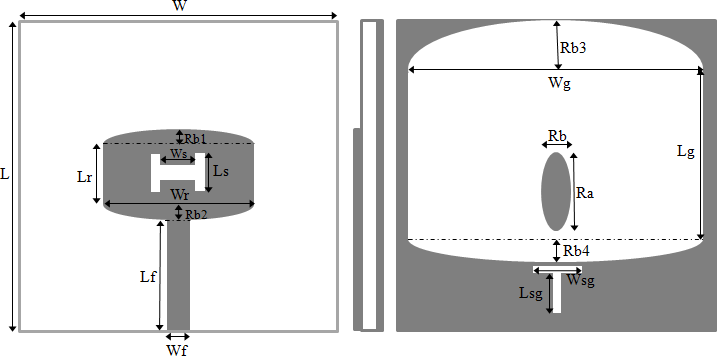


A, B, and C

###### Figure 1: Proposed antenna structures, a) square slot antenna, b) circular slot antenna, c), and proposed antenna.

The geometry of the proposed antenna is shown in Figure 1 in which the notations for the diverse dimensional elements of the antenna have been given. The antenna structure is similar to an improved rectangular radiating component comprising two half ellipses on the horizontal sides. This modification, compared to the standard rectangular shape, allows different distances between the edges and thus covers more wavelengths and increases the bandwidth of the antenna. A central '*H*' slot is added to have more degrees of freedom in the design.

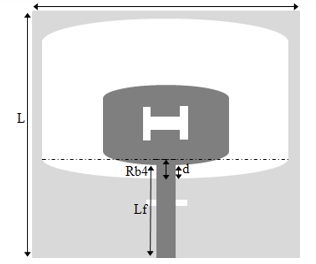
The use of the two slots, H-slot and T-slot, and the parasitic element improves and refines the performance of the antenna [9]. The signal transmission is done through a Sub-Miniature version a connector soldered to the feed line and the ground plane. The performance of the antenna depends on its geometrical parameters. Thus, because of the small size of the antenna, the lower limit of its bandwidth is above 3.1 GHz, the lower limit of the ultra-wideband standard [3.2 - 10.5 GHz]. This lower limit of the bandwidth depends largely on the lateral width (wl = w-wg), where *w* is the width of the antenna and *wg* the largest width of the ground plane slot.



A and B

###### Figure 2: Structure of the proposed ULB antenna, a) front view, b) side view

For parameters Rb4 and Lf, the joint effect of the parameters Rb4 (small radius of the lower half-ellipse of the large slot) and Lf (length of the feed line) is represented by the effect of the distance d, which is the separation distance between the bottom of the radiating element and the bottom of the large ground plane slot, as shown in Figure 3.



###### Figure 3: Explanatory diagram of the SSMA

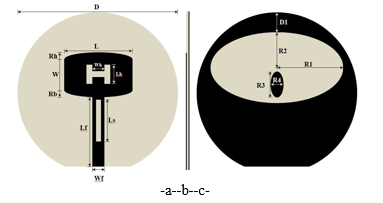
The correspondence between these quantities is given in Table I.

###### TABLE I: VARIATIONS OF PARAMETERS RB4- LF

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Rb4 (mm)** | 0.55 | 1,05 | 1,05 | 1,05 | 1.55 |
| **Lf (mm)** | 7.62 | 7.37 | 7.62 | 7.87 | 7.62 |
| **d (mm)** | 0 | 0,25 | 0.5 | 0,75 | 1.00 |

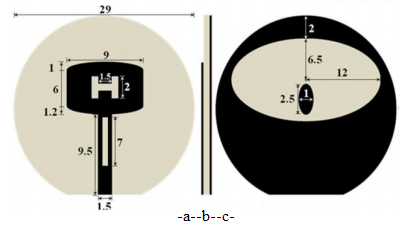
## *Directional antenna measurement and design*

The Circular Monopole Antenna with Slots (CMAS) is inspired by the SSMA; however, a circular shape has been adopted for the ground plane and the substrate. This shape allows the researchers to design a spherical sensor and thus to better resist the pressure because of the underground depth. The antenna is a circular compact planar antenna with a diameter of D = 29 mm. The radiating element is a rectangular patch with two half-ellipsoids on the horizontal sides and a central H-shaped slot. The power supply is made by a micro strip line on which a rectangular slot is made. The ground plane is a circular patch with a large ellipsoidal slot, a parasitic ellipse and a T-slot. The use of the H, T and rectangular slots and the use of the parasitic elliptical element allow for more degrees of freedom in design and also allow for further miniaturisation of the structure while maintaining acceptable performance. An optimisation taking into account the size and bandwidth trade-off was performed with the electromagnetic simulator. The antenna is designed for ULB underground application, considering the low cost PTFE NH9338 substrate and it is also common in South African market.



###### Figure 4: Proposed ULB Circular antenna structure, a) front view, b) side view, c) ground plan.

For the final structure of the sensor, the simulation analysis has allowed to obtain the optimal structure of the antenna. Figure 4 shows the antenna with its optimal dimensions. The antenna has a compact circular structure with a diameter and a radiating element of 3 dimensions, at the lowest matching frequency is 3.8 GHz.



###### Figure 5: Dimensions of the antenna a) front view, b) side view, (c) ground plan

For the bandwidth, as shown in Figure 5 the antenna has a measured reflection coefficient of less than -10 dB over a wide bandwidth (3.8 - 13 GHz) resulting in a bandwidth of about 9 GHz. │S11│ (dB) │S11│ (dB) Lf=9mm Lf=9.5mm Lf=10mm.

## *Implementation*

The omnidirectional (right) and directional antennas were embedded in the WSNs as shown in Figure 6. The final proposed antenna has a bandwidth of about 8 GHz in the 3.1 - 11.5 GHz band, omnidirectional radiation in the azimuth plane, a gain of about 3 dBi and an efficiency of 90 percent with dimensions of 7 x 4 cm. Each antenna is enfolded in a plastic film to avoid contact with water and to keep a spacing of about 1 mm around the antenna.



Figure 6: Proposed Antennas (right)

Subsequently, the implementation measurements were carried out in the lab considering two types of soil: fine sand and aggregates (ballast), which are the soil environment in most underground parts that the copper cables usually pass in South Africa. This is composed of particles with a diameter of less than 0.3 mm. At high frequencies, above 3 GHz, the relative permittivity of the different types of soil approach each other. The depth is varied underground depth between 0 and 30 cm and water content between 0% and 20%. The performance of each antenna in terms of reflection coefficient, bandwidth and input impedance is obtained for each scenario. The analysis of the impact of the underground depth on the performance of the underground antenna is performed considering a sand with a fixed average water content of 5% and dry aggregates (VWC = 0%). These water contents are those found most of the time in nature. The measurements were carried out by varying the depth, dug of 5, 10, 20 and 30 cm.

The technical characteristics of the communication chain are as follows; on the show, a generator, which is a ULB transceiver which emits pulses of 3.2 GHz bandwidth, cantered at 4.7 GHz. The pulse repetition frequency is 9.6 MHz and the effective isotropic radiated power (-12.8 dBm). This generator is computer controlled. Also, an antenna with a generator is associated with a ULB antenna with the omnidirectional antenna and the directional antenna. At the reception, the omnidirectional and directional antennas were compared. Also, a filter used in order to limit interference with other systems, and in particular 2.4 GHz, Wi-Fi, a high-pass. The filter was integrated into the reception chain. The filter adopted is a high-pass filter with a cut-off frequency of 3 GHz. The operational bandwidth is from 3 to 20 GHz, with insertion losses of less than 1 dB.

Low Noise Amplifier (LNA): Because of the low transmit power and high attenuation of the transmitted signals, a wideband low noise amplifier is added to the receive chain. This is the wideband low noise amplifier. This amplifier covers the 2 - 8 GHz band, with a gain of 23±0.5 dB and a noise figure of 1 dB. Digital Oscilloscope: to visualize and save the received signals, a wideband digital oscilloscope is placed at the end of the reception chain. This is the Infinium oscilloscope. The digital oscilloscope has a bandwidth greater than 10 GHz. We used a sampling rate of 40 Gsa/s.

### *Simulation Environment*

Two 3D electromagnetic calculators, allowing design and simulation antennas, are available at the Ansys HFSS laboratory. Time simulation Ansys helps to obtain different results in the time and frequency domains such as time signals, S-parameters, 2D and 3D radiation patterns, and electromagnetic fields in time and frequency [10]. These capacities and performances are well suited for ultra-wideband calculations, hence our choice. After making the choices mentioned above, the study designed different antenna testing stations that the experiment then utilised for the analysis of the impact of the ground on the proposed SSMA ULB and CMAS.

## *Signal transmission*

The generator for the simulation is a Gaussian pulse modulated by a sinusoid of carrier frequency, which is equivalent to 4.7 GHz. It has a time width of 0.4 ns and a spectral width of the order of 2.5 GHz at -3 dB and 4.4 GHz at -10 dB is obtained. Thus, this pulse propagates in free space over a distance of 1 m. This pulse has a temporal width of 0.53 ns and a spectral width of the order of 2 GHz at -3 dB and 3.9 GHz at -10 dB, as shown in Figure 7. The reduction in the spectral width of the received pulse compared to that of the transmitted pulse can be justified by the effect of the various components of the communication chain, including the filter and the low noise amplifier.

### *Effect of underground depth*

The analysis of the impact of the underground depth in the sand on the transmitted pulses is performed by varying the underground depth with the values d ug= 0, 5, 10, 20 and 30 cm, and by setting the water content of the soil at 5%. The results obtained for the proposed WSNs antenna and the traditional antenna are presented in Table II respectively. The maximum amplitudes of the received pulses normalised to the maximum amplitudes of the reference pulses, at d ug= 0 cm.

### *Effect of depth on signal amplitude*

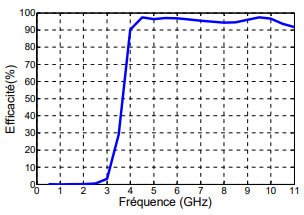
From these results, it can be seen that the maximum amplitudes of the received pulses are reduced with increasing underground depth. The magnitude of these attenuations is similar for both antennas and in both directions of communication. Effect of depth on signal shape. The analysis of the effect of the underground depth on the transmitted pulse shape is performed by calculating the fidelity factor F. The results were obtained for the two antennas (omnidirectional and directional antennas), in the two communication directions.

TABLE II: NORMALIZED PULSE AMPLITUDES

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | omnidirectional Branch Office | | Directional antennas | |
| VWC (%) | Underground-air | Air- infused | Underground-air | Air- infused |
| 0 | 0.86 | 0.88 | 0.71 | 0.79 |
| 5 | 0.71 | 0.71 | 0.53 | 0.51 |
| 10 | 0.61 | 0.56 | 0.41 | 0.43 |
| 20 | 0.40 | 0.40 | 0.31 | 0.33 |

## *H: Simulation results: Omnidirectional antennas*

The variation of wl from 1.5 to 0 mm shifts the first resonance peak of the actual components from 4.3 to 3.4 GHz, and decreases its amplitude from 100 to 80 Ω. This variation also generates a degradation of the actual part, in the 6 to 8 GHz band, which increases from 50 to 75 Ω at 7 GHz. For the imaginary part, the first resonance drops from 4.3 to 3.5 GHz, with a degradation in the 4 to 7 GHz band, or it increases from 10 to 40 Ω at 7.5 GHz. At wl = 1 mm, the actual components varies near 50 Ω with values between 35 and 75 Ω, and the imaginary part around 0 Ω with values between 22 and -22 Ω, in the 4 to 12 GHz band. Based on the reflection coefficient results the lower cut-off frequency of the passband changes from 4.3 to 3.5 GHz, as wl varies from 1.5 to 0 mm.



###### Figure 7 Antenna efficiency

The simulated efficiency of the SSMA is shown in Figure 7. The antenna has an efficiency greater than 90% over its entire operational band. The measurement is performed in an anechoic chamber, by varying the transmission frequency. The two antennas (reference and test) were fixed, face to face, at a distance of 1.5 m. The antenna has an average measured gain of 1.7 dBi in the 4 - 8 GHz band and 4.4 dBi in the 7.6 - 11 GHz band. A variance of the order of 1.7 dB is found in the 4 - 8 GHz band between the simulation and the measurement. This difference can be justified by the presence of the SMA connector and the measurement cable. A good agreement is observed in the 7.6 - 10 GHz band.

### *Antennas Frequency and Time Analysis*

The frequency behaviour of the antenna is represented by its transfer function which is obtained in this part by simulation. To obtain this characteristic, two identical free space transmit and receive SSMA antennas are considered. The two antennas are placed perpendicular to the plane containing their feed points, in the far field at 30 cm distance and in route of vision. The receiving WSNs antenna is revolved around symmetry axis with and pointed step of 44.9° for each transmission session coefficient S21, whereas the transmitting antenna is held fixed. The rotation angle holds the entire azimuth plane (H-plane) with a 0° angle where the two antennas face each other. The transmission coefficient S21 denotes the transmission function of the WSNs system consisting of the two similar transmitting and receiving antennas and the propagation in free space, in the azimuth plane. This transfer method *Hs* (*f* *)* is given by [11],[12], [14].

|  |  |
| --- | --- |
|  | (7) |

With:

|  |  |
| --- | --- |
|  | (8) |

Hc (*f,d*) is the transfer function of the free space channel. Ht (*f,t,t*) and Hr (*f,r,r*) are the transfer functions of the transmitting and receiving antennas as follows orientation respectively. For this study, working conditions of the antenna is reciprocal similar to that used by [15]:

|  |  |
| --- | --- |
|  | (9) |

It is observed that the quasi-flat shape of the transfer function curve, in the 4 to 10 GHz band, along each direction. This confirms that the transmitted signal undergoes similar attenuations throughout this frequency band in each direction, which reduces the distortion of the transmitted pulses. There is also an additional attenuation of the order of 10dB at the 90° position compared to the 0° or 180° positions. From these results and using (10), the antenna transfer function is calculated for different angular directions in the azimuth plane. It can be seen that the transfer function of the antenna is linearly increasing with frequency in the 4 to 10 GHz band and along each direction. For the 0° direction, this transfer function can be estimated by:

|  |  |
| --- | --- |
|  | (10) |

With H ( *f* ) in dB and f in GHz. This performance reduces the attenuation effect because of free space propagation, which varies in *1 / f 2*.

The computation of the spreading factor SR uses a comparison of the energy distribution of the transferred and obtained antenna pulses. The time-based width of a pulse is described as the time window with 90% of its energy [15]. For an antenna signal *vx*(t), the study defines the cumulative normalised energy function *Ev*(t):

|  |  |
| --- | --- |
|  | (11) |

Therefore, the temporal width, W(*v*), of the pulse can be given by [15].

|  |  |
| --- | --- |
|  | (12) |

Thus, the spreading factor is defined as the ratio of the temporal width of the received antenna pulse to the temporal width of the communicated pulse, such as [15]:

|  |  |
| --- | --- |
|  | (13) |

For a poorly dispersive antenna, SR is close to one. For the proposed antenna design, the simulation results obtained for SR are presented in Table III. According to these results, the spread factor of the antenna is close to 1, in the azimuthal plane, which reveals a very low dispersion behaviour and low distortion of the transmitted time pulses.

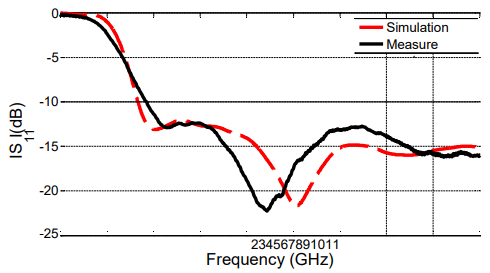
###### TABLE III: ANTENNA STRETCH FACTOR

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| *θ* | 0.0° | 91° | 181° | 271° |
| *SR* | 1,037 | 1,058 | 1,040 | 1,060 |

### *Directional antenna Simulation*

The parameters R1, R2 and D1 allow to highlight the influence of the large elliptical ground plane slot on the input impedance and the antenna matching. The variation of R1 between 11.6 mm and 12.6 mm reduces the amplitude of the first resonant peak of the actual part from 286 to 220 Ω and also shifts it in frequency from 3.4 to 3.1 GHz. For the imaginary part, there is a drop in the first resonant frequency from 4.25 to 3.75 GHz. The input impedance of the antenna is *Ze* = (51 + j16) Ω ± 21 Ω, over the 4 - 13 GHz band. For the reflection coefficient, there is a shift in the lower limit of the bandwidth from 3.9 GHz to 3.5 GHz, with a degradation of the reflection coefficient of 4 dB between 4 and 5 GHz.

The influence of the variations of D1 are reported where the real and imaginary parts of the input impedance and the reflection coefficient are represented. The input impedance can be given by: *Ze* = (56 + j16) Ω ± 31 Ω. For the reflection coefficient, there is a significant effect at high frequencies above 6 GHz. Decreasing D1 from 3.49 to 2.49 mm lowers the lower cut-off frequency from 3.7 to 4.1 GHz. For the *W* and *L* parameters, the influence of the dimensions of the radiating element on the bandwidth and input impedance variation of the *W* parameter affects the lower limit of the bandwidth. Thus, increasing *W* from 5 to 7 mm shifts the first resonance peak of the actual part of the impedance from 3.4 to 3.2 GHz, the first resonance of the imaginary part of the impedance from 3.6 to 3.3 GHz and the lower limit of the passband from 4.2 to 3.66 GHz. Thus, this change results in a 0.56 GHz bandwidth expansion.



###### Figure 8 Reflection coefficient of the antenna

The radiation of the sensor was simulated and then measured radiation pattern, which is plotted for several frequencies in Figure 8, in azimuth (a) and elevation (b). There is good agreement between the simulated and measured results. A slight difference is found between the simulation and the measurement, in the E-plane, at -90°, due to the presence of the SMA connector and the measurement cable during the characterisation. The radiation pattern is quasi-omnidirectional over the entire matching band in the azimuthal plane.

The efficiency and gain were simulated for the antenna. The CMAS presents not more than 80% efficiency on its adaptation band. Thus, this is unlike the CMAS antennas presented by the study, which obtained more than 95% efficiency gain. Besides, the gain of the antenna obtained by simulation and estimation were the antenna has an average measured gain of 2.5 dBi in the 4 - 8 GHz band, and 4 dBi in the 7.5 - 10 GHz band. There is an average difference of about 2 dB between the simulation and the measurement in the 4 - 8 GHz band, and a good agreement in the 7.5 - 10 GHz band.

### *Frequency and time analysis*

The analysis is performed by simulation using two identical CMAS antennas, transmitting and receiving, placed on the same plane with a separation distance of 40 cm. The transmitting antenna is fixed and the receiving antenna is rotated around its axis of symmetry in the azimuthal plane with a rotation step of 30°, from 0° to 360°. The transmission coefficient, S21, which denotes the transfer function of the WSNs system that has the two antennas and the propagation channel is taken for each rotation step. The ngle 0° is the position where the two antennas are in face to face position. The larger attenuations between 3 GHz and 4 GHz are due to the fact that the antenna is not well matched in this band. From the previous results and using (10), the magnitude of the antenna transfer function is obtained for each angular direction, in the 3 to 11 GHz band. Looking at the antenna transfer function along the frequency axis, it can be seen that it grows with frequency in each angular direction, with better results in the 0° and 180° directions. At 0°, the amplitude of the transfer function can be given as follows:

|  |  |
| --- | --- |
| Amplitude (dB) = -10 + 0.849 (*f*-3), *f* in GHz | (14) |

This performance reduces the effect of channel attenuation as well as dispersion and distortion of the transmitted signal. For time analysis, the modulated Gaussian pulse was used, following the same procedure as the frequency analysis. The fidelity (F) and spread (SR) factors are evaluated for each rotation point.

IV. CONCLUSION

This paper proposed the ULB antenna technique to improve underground WSNs functions. The paper used available literature, which tend to suggest that most antenna have narrow band in the 0.2 - 0.9 GHz frequency range with some work at 2.4 GHz, which tend to have poor intrusion detection capability. This is also due to the rapid increase in ground attenuation with frequency, which limits the communication range. However, these low frequency ranges imply the use of large antennas, usually quarter wave, which makes the sensor bulky and expensive and its deployment difficult and expensive. Moreover, these sensors, which are usually battery powered, consume a lot of power because the signal is continuous (CW). Moreover, due to the low bandwidth of the signals used, the localisation capacity of these systems is limited to a weak resolution. To address some of these limitations, this article focused on the ultra-wideband technology of up to 10.6 GHz. This technique allows the use of compact antennas, of a few centimetres, which favours the miniaturisation of sensors and thus facilitates their deployment. In addition, ULB regulations require very low emission levels, which limits the power consumption and allows a better lifetime of this kind of sensors. Finally, the large bandwidth of ULB signals allows high communication rates and good temporal resolution for location applications with centimetric accuracy.

## ACKNOWLEDGE

The authors would like to thank the Tshwane University of Technology for financial support. The authors declare that there is no conflict of interest regarding the publication of this paper.

# References

[1] Wang, J., Gao, Y., Liu, W., Sangaiah, A.K. and Kim, H.J., 2019. Energy efficient routing algorithm with mobile sink support for wireless sensor networks. *Sensors*, *19*(7), p.1494.

[2] Liebenberg, A. S 2021. An evaluation of the impact of the Non-ferrous Metals Crime Combating Committee on copper cable theft (Doctoral dissertation). <http://hdl.handle.net/10500/27467>.

[3] Khedo, K.K., Bissessur, Y. and Goolaub, D.S., 2020. An inland Wireless Sensor Network system for monitoring seismic activity. *Future Generation Computer Systems*, *105*, pp.520-532.

[4] Koochakkosari, A. 2019. *Energy-Efficient Integrated Circuits and Systems to Bridge the Gap between Power and Performance in Wireless Sensor Networks* (Doctoral dissertation).

[5] Barras, D. 2010. *A low-power impulse radio ultra-wideband CMOS radio-frequency transceiver* (Doctoral dissertation, ETH Zurich).

[6] Martinez, K., Ong, R. and Hart, J., 2004, October. Glacsweb: a sensor network for hostile environments. In *2004 First Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks, 2004. IEEE SECON 2004.* (pp. 81-87). IEEE.

[7] Denis, B., Keignart, J.K. and Daniele, N., 2005, September. UWB measurements and propagation models for snowy environments. In *2005 IEEE International Conference on Ultra-Wideband* (pp. 6-pp). IEEE.

[8] Croucamp, P.L., Rimer, S. and Kruger, C., 2014, July. Locomotive monitoring system using wireless sensor networks. In *2014 12th IEEE International Conference on Industrial Informatics (INDIN)* (pp. 639-644). IEEE.

[9] Das, A., Mohanty, M.N. and Mishra, R.K., 2015, October. Optimized design of H-slot antenna for bandwidth improvement. In *2015 IEEE Power, Communication and Information Technology Conference (PCITC)* (pp. 563-567). IEEE.

[10] Sturdivant, R., Quan, C., & Chang, E. (2019). Antenna Element Technology Options. In: *Systems engineering of phased arrays* (pp.125-140). Boston: Artech House.

[11] Saeidi, T., Ismail, I., Wen, W.P., Alhawari, A.R. and Mohammadi, A., 2019. Ultra-wideband antennas for wireless communication applications. *International Journal of Antennas and Propagation*, *2019*.

[12] Curiac, D.I., 2016. Wireless sensor network security enhancement using directional antennas: State of the art and research challenges. *Sensors*, *16*(4), p.488.

[13] Huang, H., Xiao, S., Meng, X., & Xiong, Y. (2010, April). A remote home security system based on wireless sensor network and GSM technology. In *2010 Second International Conference on Networks Security, Wireless Communications and Trusted Computing* (Vol. 1, pp. 535-538). IEEE.

[14] Jeong, S., Ha, D. and Tentzeris, M.M., 2013, July. A cavity-backed slot antenna with high upper hemisphere efficiency for sewer sensor network. In *2013 IEEE Antennas and Propagation Society International Symposium (APSURSI)* (pp. 49-50). IEEE.

[15] Tasouji, N., Nourinia, J., Ghobadi, C. and Mirzamohammadi, F., 2017. A novel UWB monopole antenna with controllable band-notch characteristics. *The Applied Computational Electromagnetics Society Journal (ACES)*, pp.68-73.

[16] Lim, E.K., Norizan, M.N., Mohamad, I.S., Yasin, M.N.M.,Murad, S.A.Z., Baharum, N.A. and Jamalullail, N., 2017, September. Design of anti-theft/cable cut real time alert system for copper cable using microcontroller and GSM technology. In *AIP Conference Proceedings* (Vol. 1885, No. 1, p. 020287). AIP Publishing LLC.

[17] Alejandro Granados, C., Enrique Rojas, H. and Santamaria, F., 2020. Evaluation of the Electromagnetic Shielding of Concrete from High-Frequency Simulations and the Application of the Jonscher Model. *Ingeniería (0121-750X)*, *25*(2).